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The Methyl Bromide Alternatives Outreach Conferences: Findings on Alternatives to Methyl Bromide for Select Crops Final

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OUTREACH CONFERENCES: FINDINGS ON
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1. Introduction

The Methyl Bromide Alternatives Outreach (MBAO), in cooperation with the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Agriculture (USDA), sponsors annual research conferences that attract academic researchers, growers, chemical manufacturing firms, firms manufacturing other agricultural products, and government regulators. This diverse group meets to share research results and exchange information about experiences with alternatives to methyl bromide. Presentations at the annual MBAO conferences address the advantages and disadvantages of alternatives to methyl bromide, and focus on data on farming methods, yield comparability with methyl bromide, and, occasionally, comparative costs. This paper summarizes research on a crop by crop basis, presented at the MBAO annual conferences that have been held each fall since 1995. It highlights the findings of the research presented at the conferences regarding the likely alternatives to methyl bromide, their advantages and disadvantages, and some of the remaining impediments to the adoption of likely alternatives.

1.1 Overview of Annual MBAO Conferences

The MBAO conferences have been held each November, alternately in Florida and California, since 1995. They are attended by several hundred people. In 2001, 105 presenters gave nearly 150 papers in concurrent sessions. Between 1995 and 2000, more than 100 papers addressed various aspects of alternatives for strawberries, of which 35 compared methyl bromide to one or more alternatives; 125 were relevant to tomatoes, of which 115 compared methyl bromide to alternatives. The concentration of research in these areas is not surprising, since tomato and strawberry growers are the predominant users of methyl bromide; there were fewer papers about other specific agricultural uses of methyl bromide.

The results presented at the MBAO conferences are the findings of research trials. In some cases these research trials are done on small research plots whose results may not be as efficacious in large grower fields, but in other cases the trials were done on grower-operated fields. Some of the alternatives tested are not yet available to growers, since the purpose of their testing is to determine their appropriateness as alternatives to methyl bromide. Most of the citations are from recent conferences, 1999-2001, although when no recent research is available earlier conference papers were relied upon. Full copies of the presented papers are available on the MBAO website at www.mbao.org. In addition, a searchable index of MBAO studies is posted on the EPA Methyl Bromide website at www.epa.gov/ozone/mbr.

1.2 Purpose of this Document

The purpose of this document is to provide users of methyl bromide, and other interested stakeholders, with an overview of recent research on alternatives to methyl bromide. Pertinent statements were excerpted from MBAO research papers. It is hoped that stakeholders will use this to familiarize themselves with potential alternatives.

1.3 Alternatives to Methyl Bromide

Methyl bromide controls three problems: soil-borne pests, nematodes, and weeds. Alternatives to methyl bromide need to address these problems in order to be considered for wider adoption. Currently, the most likely chemical alternatives are 1,3-D (Telone), basamid, metam sodium, and chloropicrin. The use of Telone in California is subject to township caps (see the appendix). There are other chemicals such as methyl iodide (iodomethane) and propargyl bromide that are not widely available in the U.S. since they are undergoing a regulation review process known as “registration.” Registration allows the pesticide to be used for one or more specific crops or uses. However, even when registered a chemical may not be commercially available if the company that registered the pesticide has not yet decided to produce it commercially.

To achieve broad spectrum efficacy, use of the alternative chemicals may be optimized through various processes, many of which are still being tested and are discussed in the MBAO literature. These include multiple combinations of the alternative chemicals; changes in production processes such as drip versus shank chemical applications; and use of biological controls such as crop rotation, plant growth-promoting rhizobacteria (PGPR), fallow, and solarization. Table 1 lists some of the alternatives to methyl bromide.

Table 1. Alternatives to methyl bromide.

Alternatives	Description
Armorex	A pesticide made of extracts of chili and mustard oil. It is exempt from residue tolerance.
Basamid	Also called Dazomet, is manufactured by BASF. When applied to moist soil it breaks down into methylisothiocyanate (MITC). It is used to control soil-borne pests, weeds, and nematodes. It is not as easy to use as methyl bromide because soil preparation, moisture, and temperature must be taken into account (EPA, 1995a).
Chloropicrin	Also called pic, is a fungicide manufactured by Great Lakes Chemical Corporation. It is not as effective as other substances in controlling weeds and nematodes (GAO, 1996, p. 31). Chloropicrin EC is an emulsified concentrate (Arthur et al., 2001).

Table 1. Alternatives to methyl bromide (cont.).

Alternatives	Description
Dazomet	See Basamid.
Devrinol	See Napropamide.
Diatomaceous earth	Also called DE, is defined by the UN Environment Programme (UNEP) as “abrasive fossilised remains of diatoms consisting mainly of silica with small amounts of other mineral that cause damage mainly to arthropod pests” (UNEP, 1998). At the MBAO 2001 conference it was defined as “composed of the cell walls of fossilized diatoms and can be either of freshwater or marine origin” (Arthur et al., 2001). It absorbs the wax coatings on insects so that they can’t retain moisture and die. It is used primarily for spot treatment or specific area treatment in flour mills (Milling & Baking News, March 6, 2001).
DiTera	Manufactured by Valent Biosciences, is a concentrated killed fermentation beer of the fungus <i>Myrothecium verrucaria</i> ; it has been developed for soil application (Kokalis-Burelle, 2000).
Eco2Fume	See phosphine.
Enzone	Sodium tetrathiocarbonate, is produced by Entek Corporation. It is currently registered in the US and used mainly in California for both pre-plant and post-plant soil applications on grapes, citrus, almond, peach plum, prune and roses. It controls soil nematodes, diseases, and insects (e-mail from Ely Vea, of Entek Corporation, 9/20/02).
Fosthiazate	An organothiophosphate nematicide.
InLine	Telone + chloropicrin; see Telone for further information.
Iodomethane	Also called methyl iodide and TM-425, it is manufactured by Arvesta Corporation, formerly called Tomen Agro (Allan and Schiller, 2000). It is a “broad-spectrum pre-plant soil fumigant used to control of various nematodes, soil-borne pathogens, and weed species. Soil applications are made with tractor-mounted injection equipment on flat ground, as well as into prepared plant beds or through drip injection tape within the soil bed.” It is not yet registered, but the manufacturer’s target for submission was spring of 2002 “with a potential Section 3 registration by 1st quarter 2003” (Allan and Schiller, 2001).
Messenger	A pesticide whose active ingredient is harpin protein. It is manufactured by Eden Bioscience. It is registered for numerous crops.
Metam sodium	Also called Vapam, is sodium N-methyldithiocarbamate. After it is applied and combined with water in the soil it degrades into methylisothiocyanate (MITC), which kills nematodes (microscopic unsegmented roundworms), weeds (including nutsedge), and soil-borne plant pathogens. It is registered and has been available since the 1950s. It is not as easy to use as methyl bromide. Growers need to make low-cost cropping system modifications including drip irrigation, and narrower bed widths. They must also carefully follow the label instructions.

Table 1. Alternatives to methyl bromide (cont.).

Alternatives	Description
Metam sodium (cont.)	(www.epa.gov/ozone/mbr/casestudies/volume1/metams.html page 2, quoting Noling and Becker, 1994, "The Challenge of Research and Extension to Define and Implement Alternatives to Methyl Bromide." Supplement to the <i>Journal of Nematology</i> , Vol. 26, No. 4, pp. 573-586).
Methyl iodide	See Iodomethane.
Methylisothiocyanate	See MITC.
MITC	Methyl isothiocyanate is the degenerative product of both metam sodium and basamid. It is used to control weeds, insects, fungi, and nematodes (Woodrow et al., 1998). According to a GAO report, it is a potential groundwater contaminant (GAO, 1996, p. 30).
Napropamide	Also called Devrinol, it is a herbicide that has been tested in research trials on peppers and strawberries (Eger, 2000). It is manufactured by United Phosphorus.
Pebulate	S-propyl buty(ethyl)thiocarbamate, is also called Tillam. It is manufactured by Helena Chemical Company. It is a selective herbicide, often used to control the weed nutsedge (Nelson et al., 1999; Eger, 2000). It is registered for use on tomatoes.
PGPR	Plant-growth-promoting rhizobacteria live on the roots of plants; they enhance growth and sometimes induce disease resistance. PGPR are not available commercially at this time (Eayre, 2001).
Phospine	Also marketed as Eco2Fume. It is manufactured by Cytec in Niagara Falls, Canada. Aluminum or magnesium phosphide pellets react with moisture in the air to produce phosphine gas. It is also sold in cylinders combined with carbon dioxide, which prevents spontaneous combustion, a hazard with pellets (Milling & Baking News, March 6, 2001, available at www.epa.gov/ozone/mbr/infclear.html). It is used most often to fumigate grains and grain silos and structures; it is toxic to fresh fruits and vegetables (GAO, 1996, pp. 33-34).
Plantpro 45	An iodine based compound manufactured by Ajay North America; it is not (yet) registered (Kokalis-Burelle, 2000).
PPO	See propylene oxide.
PrBr	See propargyl bromide.
ProFume	See sulfuranyl fluoride.
Propargyl bromide	Patented by Dow Chemical Co. in 1957 but taken off the market. In 1999, Albemarle Corporation expressed an interest in developing it as an alternative to methyl bromide. "Preliminary field efficacy trials were carried out in 2000. These initial studies indicated good efficacy against soil pathogens. . . . The field and microplot studies are being repeated this year" (Trout, 2001).
Propozone	See propylene oxide.
Propylene glycol	See propylene oxide.

Table 1. Alternatives to methyl bromide (cont.).

Alternatives	Description
Propylene oxide (PPO)	A fungicide that converts to propylene glycol in the soil. It performs best when shank applied. PPO is registered for use on food and for the control of stored pests (Norton, 2001).
Rezist	A fertilizer composed of zinc, copper and manganese. It is manufactured by Stoller Enterprises.
Solarization	Involves laying down clear plastic over damp soil to trap solar radiation and heat the soil. Solarization works by raising the soil temperature enough to kill soil-borne pests. The plastic stays in place for a number of weeks. It can be used only in warm climates or in the summer when sunlight is strong (USDA, 1998).
Sulfuryl fluoride	Also called ProFume and Vikane, is sprayed as a liquid but converts to a gas, and is used for wood-destroying pests and to fumigate empty structures such as warehouses (GAO, 1996, p. 34). Dow Chemical is working to register it for dried fruit and nut uses; they expect EPA registration and marketing in 2003 (Milling & Baking News, March 6, 2001).
Telone	Also called 1,3-D and Telone II, is 1,3-dichloropropene. It is manufactured by Dow Chemical Company of Midland, Michigan. Mixtures of Telone and Chloropicrin include Telone C-17 which contains 17% pic, and Telone C-35, which is 35% pic (e-mail from J. Gilreath, University of Florida, Gulf Coast Research and Education Center, 10/23/02). Telone is registered for use on a number of crops including strawberries and tomatoes.
Tillam	See Pebulate.
TM-425	See Iodomethane.
Treflan	See Trifluralin.
Trifluralin	A dinitroaniline herbicide. Also called Treflan.
Vapam	See Metam sodium.
VIF	Virtually impermeable plastic film used as a mulch.
Vikane	See sulfuryl fluoride.

1.4 Literature Review Approach

The MBAO conference proceedings from 1999-2001 were reviewed to identify those studies that examined alternatives to methyl bromide for strawberries; tomatoes; tree fruits and nuts; forest, sod, ornamentals, and nurseries; and post-harvest uses. The relevant studies were further examined to obtain information about the efficacy of the alternative in comparison to methyl bromide. Efficacy was defined by yield in most cases, and weed or pest control in the absence of information on yield. This document discusses the alternatives being studied for each of the above uses, and presents brief excerpts from the articles on the findings of the studies. References are provided in each case that allows readers to explore the detailed articles. A

summary table is provided for each section that identifies by the alternative examined, each study and its findings on efficacy.

2. Strawberries

California growers produce over 80% of the strawberries in the United States, Florida is second, with about 12%. Strawberries are the fourth most valuable fruit crop in the United States, after grapes, apples, and oranges (Carter et al., 2002, p. 4). The problems strawberry growers face are weeds, soil-borne pests, and nematodes. More than “about 93% of the MeBr use in California was for pre-plant soil fumigation. . . . The primary crops for which methyl bromide is used include strawberries [which account for] 32% of the total soil fumigation” (Trout, 2000). With the ban on methyl bromide, other problems faced by growers are possible decreases in yield and/or increases in costs, the possibility of having to learn new production methods, the possible increases in time needed to apply alternatives and wait for the pesticides to take effect/dissipate, and worker safety when applying these very toxic substances.

A number of chemical alternatives are being tested, and research is also being conducted on different application processes (drip versus shank applications) and on organic farming practices. The research indicates that most promising registered alternatives to methyl bromide for strawberries are basamid (dazomet), chloropicrin, metam sodium, and Telone. Alternatives that have been researched but are not registered for use on strawberries are devrinol (napropamide), enzone, methyl iodide (iodomethane), pebulate, Plantpro 45, propargyl bromide, and propylene oxide.

In the 1999-2001 MBO research conferences in the past three years, strawberries were the subject of 18 studies comparing yields using methyl bromide with alternatives. The registered alternatives include basamid, chloropicrin, metam sodium, and Telone. Common nematocides include Devrinol, Enzone, Fosthiazate, and trifluralin.

Five studies tested basamid alone or in combination with other substances in California and Florida. All indicated that basamid gives yields comparable to those achieved with methyl bromide + chloropicrin. A great deal of research has been done on Telone in various combinations with chloropicrin. In 20 of the 22 studies using this combination, yields were at least comparable to those achieved with methyl bromide + chloropicrin. Research was conducted in both California and Florida. Telone and chloropicrin combined with basamid or with metam sodium gave yields equal to or better than those achieved with the methyl bromide combination; there were two studies with basamid and nine with metam sodium.

Chloropicrin is frequently combined with other substances. It was tested alone in six trials; it gave comparable results to methyl bromide in four studies. Shank-applied chloropicrin alone was as effective as methyl bromide + chloropicrin; when it was drip applied, the yields were less. Drip-applied chloropicrin EC (emulsified concentrate) gave nearly comparable results in one study and comparable results in another.

Among the nematocides, using Devrinol without other alternatives resulted in yields lower than those achieved with methyl bromide in one study. DiTera was the subject of two studies, both of which found it comparable in California when combined with metam sodium and chloropicrin. Enzone was the subject of two studies: in one it was combined with basamid and chloropicrin, in the other with metam sodium and chloropicrin; in both studies yields were comparable to those achieved with methyl bromide + chloropicrin. Fosthiazate when combined with metam sodium and chloropicrin EC gave comparable yields. PGPR (plant growth promoting rhizobacteria), the subject of one study, were found to be efficacious but are not commercially available.

Unregistered alternatives studied were iodomethane, propargyl bromide, and sulfuryl fluoride. Iodomethane alone or combined with chloropicrin gave comparable or better yields in both California and Florida in all 10 of the studies reported. Propargyl bromide gave comparable results in one part of California and less than comparable yields in another situation in the two studies reported in 2001.

The conclusion from these studies is that there are alternatives for methyl bromide that produce yields at least as high as methyl bromide. Further, many of these alternatives can be used with drip irrigation; a switch from shank to drip irrigation is not expected to be difficult and has some side benefits for worker safety and ease of application of multiple substances. Over the years, as research has gotten more sophisticated, the relative mixes of alternatives have proven more and more efficacious.

The following paragraphs identify specific findings from the MBAO conferences on the efficacy of methyl bromide alternatives for strawberries. A number of papers reported comparable or better results from the use of alternatives to methyl bromide, and few reported significant differences. It is noteworthy that the more current research findings indicate comparable yields between methyl bromide and its alternatives as compared to earlier years. This could be a result of using different concentrations and application processes based on earlier experiences.

2.1 MBAO Conference — 2001

- 2.1.1 Ferguson et al. conducted field trials in North Carolina and Georgia of various chemicals: chloropicrin, Telone, metam sodium, and iodomethane. In the North Carolina trials,

marketable yields comparable (not statistically different) to those obtained with methyl bromide were obtained using Telone-C35, Inline (Telone), metam sodium, metam sodium (drip), chloropicrin, iodomethane (100%), and iodomethane:chloropicrin (60:40) treatments. However, Telone II (a different amount applied) and compost produced lower yields. In Georgia, yields equivalent to methyl bromide resulted from Inline + metam sodium, Telone C-35 + metam sodium, Telone II + metam sodium. In Georgia, the herbicide Devrinol with soil fumigants produced significantly lower yields in comparison to methyl bromide (Ferguson et al., 2001).

- 2.1.2 Field trials were conducted during the 2000-2001 strawberry growing season in California (Oxnard and Salinas) and Florida (Chancey and Duke) as part of the USDA's IR-4 Project (Interregional Research Project) to identify alternatives to methyl bromide. Nelson et al. (2001) reported that "in the Oxnard trials, treatments which produced a mean yield statistically comparable to the mb/pic [methyl bromide:chloropicrin] standard (67/33 at 300 lbs) were iodomethane/chloropicrin (60/40 at 295 lbs), chloropicrin EC alone (300 lbs), Inline alone (32 gals), and combinations of Basamid + chloropicrin (at 200 lbs and 300 lbs, respectively), Basamid + Enzone + chloropicrin EC (at 200 lbs, 94 ozs/100 gals of irrigation water, and 200 lbs, respectively), metam sodium + Inline (at 37.5 gals, and 32 gals, respectively), metam sodium + chloropicrin EC + Fosthiazate (at 37.5 gals, 200 lbs, and 4.5 lbs ai [active ingredient] respectively, metam sodium + chloropicrin EC + DiTera DF (at 37.5 gals and 200 lbs and 12 lbs - pre- and post-planting, respectively) and metam sodium and Propozone (at 37.5 gals and 100 gals, respectively). . . . Metam sodium was used strictly for weed control. . . . Results from the statistical analyses of the Chancey (Florida) trial marketable fruit yield are comparable to the Oxnard (California) trial. At the Duke (Florida) trial, all . . . treatments resulted in marketable fruit yields comparable to the methyl bromide standard, except Plantpro 45 B combinations" (Nelson et al., 2001). Salinas trial results were not available.
- 2.1.3 Sances presented research conducted over several years. "These data present the sixth year of field tests of alternative chemical fumigation, greenhouse grown strawberry plug plants and an organically acceptable production program for California. Soil fumigation was conducted with several fumigants on strawberry, tomatoes and floricultural crops. . . . Iodomethane alone and in combination with chloropicrin and Telone/chloropicrin were acceptable alternatives to methyl bromide. [They] gave acceptable levels of control of soil pathogens, as well as producing yields equal to or better than methyl bromide/chloropicrin. . . . Weed control was good to excellent with Iodomethane" (Sances, 2001).

- 2.1.4 Cynthia Eayre (2001) from the USDA presented a paper on PGPR. Eayre stated, “Preliminary trials included screening of 130 PGPR (plant growth promoting rhizobacteria). Advanced trials . . . tested for additional increase in yield when soil fumigation was followed by treatment with PGPR at planting. . . . The results are consistent with earlier results, and with the results of other researchers. Yield in plots with pic [chloropicrin] treatment alone is slightly less than methyl bromide alone. . . . Surprisingly, yield in some of the pic plus PGPR plots is even higher than in methyl bromide plots. . . . PGPR lend themselves to application through the drip irrigation system. . . . Little or no additional equipment is needed since many growers already apply fertilizer through the irrigation system. Strawberry yields achieved with this combination of treatments are equal to or better than those achieved with methyl bromide.” However, these PGPR are not commercially available.
- 2.1.5 Driver et al. (2001) examined drip versus shank application and concluded that drip irrigation was better than shank injection. “In evaluating the feasibility of drip irrigation applications of chemicals for the control of soil-borne pathogens in strawberry and vegetables, there are several potential advantages to the approach. Advantages: 1) economical, 2) more environmentally friendly, 3) reduced worker exposure, 4) reduced amounts of chemicals applied, 5) effective, 6) potential in double-cropping systems and 7) flexibility of timing. . . . [However,] there are some potential problems. . . . Disadvantages: 1) single vs. double tapes, 2) depth of tape, 3) variation in soil types, 4) variation in moisture, 5) mobility through soil profile, 6) safety of water sources 7) time. . . . Drip and shank applied metam sodium and Telone-C35 or Inline (drip) treatments were evaluated during the 2000-2001 strawberry season at Plymouth, NC, Clayton, NC and Vidalia, GA. Yields and quality of fruit, plant growth and root rot severity were monitored for comparison of these treatments. At these Plymouth and Clayton marketable yields of Telone-C35 shank-applied versus Inline drip-applied treatments were both equivalent to yields obtained with MB [methyl bromide + chloropicrin] (67:33). Shank injection/ tilled applications of vapam [metam sodium] and drip irrigation applications of vapam provided equivalent yields to MB at Plymouth and Vidalia.”
- 2.1.6 One study in 2001 showed higher strawberry yields in some cases and lower yields in others when using alternatives. Ajwa et al. (2001) conducted a study where the objective of the study was to determine the most efficacious application rate and method of application of iodomethane:chloropicrin mixture and propargyl bromide (PrBr) for strawberry production in California. “For most application rates, strawberry yields from drip fumigation were greater than yields from shank injection treatment.” While drip irrigation with iodomethane:chloropicrin and propargyl bromide provided comparable results to methyl bromide in Watsonville, CA, only iodomethane:chloropicrin provided

similar results in Salinas, CA. “Reduced yields [observed] in the PrBr treatments in the Salinas soil were attributed to phytotoxicity.” The authors contend that cool climate and soil type in Salinas may have delayed the dissipation/degradation, and therefore efficacy, of propargyl bromide.

2.2 MBAO Conference — 2000

- 2.2.1 The 1999-2000 USDA IR-4 methyl bromide alternatives yielded results similar to the ones reported in 2001. Nelson et al. (2000) reported that “in the CA trials, treatments which produced a mean yield (average from two trials) statistically comparable to mb/pic (67/33) were: iodomethane/chloropicrin (67/33 at 350 lbs. and 50/50 at 235 lbs. per acre), Enzone + chloropicrin (EC) + metam sodium (at rates of 48.2 ozs. per 100 gals. irrigation water - preplant, 200 lbs. per treated acre and 37.5 gals. in 1000 gals. water carrier per treated acre, respectively), the two InLine combination treatments (applied at 38.4 gals. per treated acre and combined with either metam sodium at 37.5 gals. in 1000 gals. water carrier as a broadcast bed-top spray or with Basamid, applied at 200 lbs. per treated acre also over the bed-top and incorporated with water), and a combination treatment of DiTera + chloropicrin (EC) + metam sodium (at rates of 8 gals, 200 lbs. and 37.5 gals. per treated acre, respectively). In the Enzone and DiTera combination treatments, the approach here was to combine the nematicidal properties of these products with the fungicidal activity of chloropicrin, and the general biocidal activity of metam sodium as a soil surface broadcast spray over the bed-top strictly for weed control (applied just prior to application of the plastic bed mulch). With the InLine combination treatments, either metam sodium or Basamid was used to target weed seeds in the bed-top. . . . Similar results were obtained from the two Florida trials, with the following treatments producing a mean marketable fruit yield (averaged from two trials) statistically comparable to the mb/pic standard: both treatments of iodomethane/chloropicrin (67/33 and 50/50 at 350 and 235 lbs. per treated acre, respectively), and the two Telone C35 combination treatments (C35 shank applied at 35 gals. per treated acre and combined with either metam sodium or Basamid, applied to the bed-top).”
- 2.2.2 Chemical alternatives to methyl bromide were tested in replicated field experiments at a coastal site near Watsonville and results reported. Duniway et al. (2000) reported that “with standard plastic mulch, chloropicrin at 200 lb/a and Telone C-35 at 283 and 425 lb/a, when shank- or drip-applied, gave yields as high as or higher than those obtained with MBC [methyl bromide/chloropicrin]. Use of VIF [virtually impermeable plastic film] plastic mulch, however, increased yields significantly in all chloropicrin treatments and in some Telone C-35 treatments.”

- 2.2.3 The yield of methyl bromide alternatives was examined by a farmer in Oxnard, California. Martinez et al. (2000) found that “Chloropicrin + MS (metam sodium) and chloropicrin alone yielded 85% and 90% of the standard methyl bromide + chloropicrin treatment respectively (Table 1). Telone C35 + MS (metam sodium) and chloropicrin EC + MS (metham sodium) yielded 100% and 102% of the standard methyl bromide + chloropicrin treatment respectively. Inline, Telone C35, chloropicrin EC and Inline + MS yielded 119%, 122%, 124% and 126% of the standard methyl bromide + chloropicrin treatment respectively. Chloropicrin EC and Inline containing treatments had higher early yields than the standard methyl bromide + chloropicrin treatment, and also higher early yields of shank-applied chloropicrin or Telone C35. The treatments containing 600 lb/A chloropicrin shank-applied resulted in the lowest yields, possibly due to injury from the very high rate of chloropicrin carryover.” The authors, while reporting that the alternatives show promise, also discuss some of the regulatory, cultural, and time barriers that make it difficult to switch to methyl bromide alternatives.
- 2.2.4 Ajwa and Trout (2000) compared methyl bromide, Telone, and metam sodium; for each alternative they also compared shank injected and drip application methods. They found that “‘long-term’ application of Inline, CP EC [chloropicrin EC], and sequential application of reduced rates of these fumigants with metam sodium shows promise in . . . producing strawberry yields nearly comparable to present production (methods) with methyl bromide. This [drip] application method can reduce costs because separate application equipment is not required. It is expected to be safer than present methods of shank injection because workers are not required to be in the field during application.”
- 2.2.5 Sances (2000) reported on trials during 1999-2000 in which he compared methyl bromide with Telone/pic and iodomethane/pic. He found that “Telone/chloropicrin and Iodomethane/chloropicrin performed very well with season yields overall. The cost of application of alternative fumigants was less than either methyl bromide/chloropicrin or the Organic program, as a result of the use of reduced rate drip application technology employed. In current dollars, at the rates used in this study, the cost of methyl bromide/chloropicrin broadcast fumigation is approximately \$1400/ac, compared to \$800/ac for Telone/chloropicrin applied in this manner.” The cost for Iodomethane at the rates used in this study is currently unknown.
- 2.2.6 TM-425 (Iodomethane) is a broad spectrum fumigant developed by Tomen Agro, Inc. (now Arvesta Corporation), and was submitted for EPA registration in 2002. A decision on its status is expected in late 2002 or in 2003. It is applied to the soil for control of various soil-borne fungi, nematodes, and weed species in strawberry, tomato, and flower production acreage. A study by Tomen Agro, Inc. indicates that data from various field

trials show TM-425 in combination with chloropicrin results in increased yields in comparison to methyl bromide with chloropicrin (Allan and Schiller, 2000).

- 2.2.7 Eger (2000) reported that in Florida, in strawberry trials conducted from 1993 to 1999, yields resulting from the use of Telone products were about 98% of those with methyl bromide/chloropicrin, a difference that is probably not statistically significant. Telone products with a herbicide resulted in a nutsedge control comparable to methyl bromide + chloropicrin in about 90% of the observations, and when grasses and broadleaf weeds were included, the control was comparable in 100% of the observations.
- 2.2.8 One study reported strawberry yields that were significantly less than that associated with methyl bromide. In 1997, Fernandez et al. initiated field trials in North Carolina to examine alternatives for strawberry production (Fernandez et al., 2000). They reported that the solarized, T-C35, and Vapam (metam sodium) plots all had larger average berry size than methyl bromide treated plots in the first year. However, “in the second year, yield in the solarized plots and the (first year) compost plots were low and this yield decline continued in Year 3 in the solarization-based plots. In contrast, the compost-based plots were similar to the MB-treated plots after the second year of compost application. Vapam treated plots generated consistent yields throughout all 3 years. The Telone C-35 plots demonstrated a tendency to decline in Year 2; in Year 3 phytotoxicity was observed on strawberry plants soon after transplanting. In Year 3, the Plymouth region was subject to 2 hurricanes during the fall of 1999 and excess moisture delayed proper scheduling of fumigant applications, compressed waiting periods for planting after fumigation, and a delay in field setting plants beyond the optimum date for this region. These factors resulted in substantial reductions in total yield and the phytotoxicity observed in the Telone C-35 plots.”

2.3 MBAO Conference — 1999

- 2.3.1 Sances and Ingham (1999) gave a report that included alternative fumigation regimes field tested in California over the previous five years. They described their procedures: “Following fumigation, the highly disease susceptible UC cultivar Camerosa was planted. . . . Across all years, the best performing fumigant was Telone/chloropicrin at 30-35% chloropicrin. These results were consistent for both loam and clay soils among the five years. . . . Performance of Telone/chloropicrin was not impacted by soil type and yields were only 5-8% less than those of methyl bromide/chloropicrin.”

- 2.3.2 The California Strawberry Commission and University of California Statewide IPM Project funded research to study chemical and nonchemical alternatives to methyl bromide for preplant fumigation of soil in strawberry production (Duniway et al., 1999). Chemical alternatives were tested at a coastal site near Watsonville, California. Duniway et al. reported “yields in 1998 and 1999, respectively, relative to those obtained following standard bed fumigation with methyl bromide/chloropicrin (MBC, 67/33% @ 325 lb/acre), were 77 and 98% for chloropicrin alone (300 lb/acre). . . . Shank applied chloropicrin at 200 and 300 lb/acre gave yields nearly equivalent to those obtained with MBC, but drip-applied chloropicrin at 200 lb/acre was somewhat less effective; VIF mulch did not improve yields in the chloropicrin treatments. Results with Telone/chloropicrin (C35) were more variable, but shank applications to beds at 283 and 425 lb/acre with standard mulch gave yields nearly equivalent to MBC, and there was no benefit of VIF in these treatments. Drip applications of Telone/chloropicrin were slightly less effective, but VIF mulch improved yields with drip-applied Telone/chloropicrin.”
- 2.3.3 A study was conducted at Gainesville and Quincy in Florida to evaluate the effects of soil fumigants and solarization on strawberry production (Locascio et al., 1999). The authors reported that “. . . the yield with methyl bromide-chloropicrin was statistically similar to that with 1, 3-dichloropropene [Telone] + 17% chloropicrin. . . . In summary, early plant growth and yields at Gainesville were poorer than expected, probably due the high incidences of fungal root diseases and to excessive rainfall during Dec. to Mar. The yield with MBr-Pic was statistically similar to that with 1,3-dichloropropene + 17% Pic (C-17), C-35, Pic, and soil solarization + metam sodium + mulch painted black before transplanting. Yields were significantly lower with the check, metam sodium, metam sodium + chloropicrin, and soil solarization-mulch painted before planting than with MBr-Pic. At Quincy, plant growth was excellent and yields were statistically similar with Pic, MBr-Pic (67:33), dazomet, solarization + dazomet with mulch painted black, Telone C-17, Telone C35, and metam sodium + chloropicrin.”
- 2.3.4 Soil fumigants 1,3-dichloropropene (1,3-D) (Telone) in combination with chloropicrin (Telone C35), chloropicrin alone, and metam sodium (Vapam) were studied in strawberry production in Watsonville and Salinas (Trout and Ajwa, 1999b). They reported that “generally [in Watsonville], shank-applied MeBr and Telone C-35 gave the best yields, followed closely by the full rate drip-applied Telone + Chloropicrin (Inline) treatments. Reduced rate Inline, even in combination with Vapam, gave inconsistent results at this site. Chloropicrin at the low rates used (160 lb/ac) and Vapam were also unable to control the pest pressures. . . . Vapam injected simultaneously with Telone or chloropicrin did not show the expected synergism. Metam Sodium and chloropicrin and/or 1,3-D may have reacted in the aqueous solution resulting in rapid degradation/hydrolysis of the metam sodium. . . . At Salinas in 1998, all treatments, including the

non-treated control, showed little soil-borne pest pressure and yields were relatively uniform for all treatments. At this site, nearly all drip-applied treatments tended to out-produce the shank-applied fumigants. Drip-applied Inline, at full rates, gave a 10% - 20% yield boost compared to the MeBr standard.”

Table 2. Alternatives to methyl bromide for use on strawberries.

Alternative	Citation	Number in Section 2	Efficacy information
Basamid + chloropicrin	Nelson et al., 2001 (#43)	2.1.2	Comparable to methyl bromide
Basamid + Telone + chloropicrin	Nelson et al., 2000 (#3)	2.2.2	Comparable to methyl bromide
Basamid + Telone C35	Nelson et al., 2000 (#3)	2.2.2	Comparable to methyl bromide
Basamid + Enzone + chloropicrin	Nelson et al., 2001 (#43)	2.1.2	Comparable to methyl bromide
Basamid (dazomet), also with solarization and mulch painted black	Locascio et al., 1999 (#5)	2.3.3	Comparable to methyl bromide
Chloropicrin	Ferguson et al., 2001 (#42)	2.1.1	Comparable to methyl bromide
	Nelson et al., 2001 (#43)	2.1.2	Comparable to methyl bromide
	Eayre, 2001 (#100)	2.1.4	Yield slightly less than methyl bromide
	Martinez et al., 2000 (#11)	2.2.3	85-90% of methyl bromide, but 124% of methyl bromide with emulsified concentrate (EC) form
	Ajwa and Trout, 2000 (#25)	2.2.4	Nearly comparable to methyl bromide
	Duniway et al., 1999 (#2)	2.3.2	77% of methyl bromide in 1st year, 98% in second year
	Locascio et al., 1999 (#5)	2.3.3	Comparable to methyl bromide
Chloropicrin with VIF plastic mulch (shank or drip applied)	Duniway et al., 2000 (#9)	2.2.2	Better than methyl bromide

Table 2. Alternatives to methyl bromide for use on strawberries (cont.).

Alternative	Citation	Number in Section 2	Efficacy information
Chloropicrin with standard plastic mulch (shank or drip applied)	Duniway et al., 2000 (#9)	2.2.2	Comparable to methyl bromide
Devrinol + soil fumigation	Ferguson et al., 2001 (#42)	2.1.1	Lower than methyl bromide
Iodomethane (100%)	Ferguson et al., 2001 (#42)	2.1.1	Comparable to methyl bromide
	Sances, 2001 (#45)	2.1.3	Better than to methyl bromide
Iodomethane + chloropicrin	Ferguson et al., 2001 (#42)	2.1.1	Comparable to methyl bromide
	Nelson et al., 2001 (#43)	2.1.2	Comparable to methyl bromide
	Sances, 2001 (#45)	2.1.3	Better than methyl bromide
	Ajwa et al., 2001 (#24)	2.1.6	Comparable to methyl bromide
	Nelson et al., 2000 (#3)	2.2.1	Comparable to methyl bromide
	Sances, 2000 (#24)	2.2.5	Comparable to methyl bromide
	Allan and Schiller, 2000 (#36)	2.2.6	Higher yields than methyl bromide
Metam sodium (vapam)	Ferguson et al., 2001 (#42)	2.1.1	Comparable to methyl bromide
	Driver et al., 2001 (#87)	2.1.5	Comparable to methyl bromide
	Fernandez et al., 2000 (#35)	2.2.8	Better than methyl bromide in first year, lower in second year, perhaps due to hurricanes
	Locascio et al., 1999 (#5)	2.3.3	Lower than methyl bromide

Table 2. Alternatives to methyl bromide for use on strawberries (cont.).

Alternative	Citation	Number in Section 2	Efficacy information
Metam sodium + chloropicrin	Martinez et al., 2000 (#11)	2.2.3	85-90% of methyl bromide; comparable to methyl bromide (100-102%) when using drip application.
	Ajwa and Trout, 2000 (#25)	2.2.4	Nearly comparable to methyl bromide
	Locascio et al., 1999 (#5)	2.3.3	Lower than methyl bromide at Gainesville; comparable to methyl bromide at Quincy
Metam sodium + chloropicrin EC + DiTera DF	Nelson et al., 2001 (#43)	2.1.2	Comparable to methyl bromide
	Nelson et al., 2000 (#3)	2.2.1	Comparable to methyl bromide
Metam sodium + chloropicrin EC + Enzone	Nelson et al., 2000 (#3)	2.2.1	Comparable to methyl bromide
Metam sodium + chloropicrin EC + Fosthiazate	Nelson et al., 2001 (#43)	2.1.2	Comparable to methyl bromide
Metam sodium + Propozone	Nelson et al., 2001 (#43)	2.1.2	Comparable to methyl bromide
Metam sodium + solarization + mulch painted black before transplanting	Locascio et al., 1999 (#5)	2.3.3	Comparable to methyl bromide
PGPR (plant growth promoting rhizobacteria)	Eayre, 2001 (#100)	2.1.4	Comparable to or better than methyl bromide
Plantpro 45 B	Nelson et al., 2001 (#43)	2.1.2	Lower than methyl bromide
Propargyl bromide (PrBr)	Ajwa et al., 2001 (#24)	2.1.6	Comparable to or lower than methyl bromide depending on soil and climate
Telone	Eger, 2000 (#40)	2.2.7	Comparable to methyl bromide (98%)
Telone II	Ferguson et al., 2001 (#42)	2.1.1	Lower than methyl bromide

Table 2. Alternatives to methyl bromide for use on strawberries (cont.).

Alternative	Citation	Number in Section 2	Efficacy information
Inline (Telone + chloropicrin)	Ferguson et al., 2001 (#42)	2.1.1	Comparable to methyl bromide
	Nelson et al., 2001 (#43)	2.1.2	Comparable to methyl bromide
	Sances, 2001 (#45)	2.1.3	Yields equal to or better than methyl bromide
	Driver et al., 2001 (#87)	2.1.5	Comparable to methyl bromide
	Martinez et al., 2000 (#11)	2.2.3	119% of methyl bromide
	Sances, 2000 (#24)	2.2.5	Performed very well compared to methyl bromide
	Sances et al., 1999 (#9)	2.3.1	92-95% of methyl bromide
	Duniway et al., 1999 (#2)	2.3.2	Shank application comparable to methyl bromide; drip application with VIF mulch comparable to methyl bromide
Inline (Telone + chloropicrin) drip Telone C35	Locascio et al., 1999 (#5)	2.3.3	Comparable to methyl bromide
	Ajwa and Trout, 2000 (#25)	2.2.4	Nearly comparable to methyl bromide
	Ferguson et al., 2001 (#42)	2.1.1	Comparable to methyl bromide
	Driver et al., 2001 (#87)	2.1.5	Comparable to methyl bromide
	Martinez et al., 2000 (#11)	2.2.3	122% of methyl bromide
	Fernandez et al., 2000 (#35)	2.2.8	Better than methyl bromide in first year, lower in second year, perhaps due to hurricanes
	Locascio et al., 1999 (#5)	2.3.3	Comparable to methyl bromide
	Trout and Ajwa, 1999b (#10)	2.3.4	Comparable to methyl bromide

Table 2. Alternatives to methyl bromide for use on strawberries (cont.).

Alternative	Citation	Number in Section 2	Efficacy information
Telone C35 with standard plastic mulch (shank or drip applied)	Duniway et al., 2000 (#9)	2.2.2	Comparable to methyl bromide
Telone C35 + metam sodium	Ferguson et al., 2001 (#42)	2.1.1	Comparable to methyl bromide
	Nelson et al., 2000 (#3)	2.2.2	Comparable to methyl bromide
	Martinez et al., 2000 (#11)	2.2.3	Comparable to methyl bromide (100-102%)
Inline (Telone + chloropicrin) + metam sodium	Ferguson et al., 2001 (#42)	2.1.1	Comparable to methyl bromide
	Nelson et al., 2001 (#43)	2.1.2	Comparable to methyl bromide
	Nelson et al., 2000 (#3)	2.2.1	Comparable to methyl bromide
	Martinez et al., 2000 (#11)	2.2.3	126% of methyl bromide
Inline (Telone + chloropicrin) + metam sodium drip	Ajwa and Trout, 2000 (#25)	2.2.4	Nearly comparable to methyl bromide
Telone C35 + metam sodium + <i>B. subtilis</i> .	Ferguson et al., 2001 (#42)	2.1.1	Comparable to methyl bromide

3. Tomatoes

Methyl bromide is used on tomatoes in Florida, Georgia, South Carolina, North Carolina, and in small quantities in a few other states. Florida is the largest user of methyl bromide for this crop. The state's fresh market tomatoes and peppers account for about one-third of the methyl bromide used for soil fumigation (USDA, 1998). Tomato growers use methyl bromide to address weeds, soil-borne pests, and nematodes. The following alternatives are registered for use on tomatoes: chloropicrin, metam sodium, pebulate, and Telone. Research presented at the MBO conferences has been concerned with all of these substances. In addition, there has been considerable research using methyl iodide (not yet registered for crop use) and some on napropamide (Devrinol) for weed control. Other unregistered alternatives subject to research are Plantpro 45, Plantpro 20, propargyl bromide and trifluralin, Messenger, and Rezist. Solarization,

crop rotation, and resistant cultivars are nonchemical alternatives that may also be used alone or in conjunction with the chemicals.

Seventeen research studies examining the efficacy of alternatives to methyl bromide for tomatoes, including comparative yields, were presented at the 1999-2001 MBAO conferences. Four of the six studies with metam sodium alone or in combination with Telone reported yields equivalent to or better than those achieved with methyl bromide. In two of the studies, yields were less than those achieved with methyl bromide. In general, researchers who worked with metam sodium found that to obtain the best yields it was important to follow the label instructions.

Telone combined with chloropicrin was the subject of 11 studies; in all of them yields were as high or higher than those achieved with methyl bromide. Combining Telone and chloropicrin with metam sodium and pebulate, a herbicide efficacious for nutsedge, resulted in lower yields in a 1999 study but comparable or higher yields in four subsequent studies. In one study in 2001, napropamide (Devrinol) combined with chloropicrin resulted in yields lower than those achieved with methyl bromide.

Methyl iodide, not yet registered, is a promising alternative to methyl bromide. Five studies in 2001 involving methyl iodide alone and in combination with chloropicrin produced yields comparable to and better than those achieved with methyl bromide. The registration of propylene oxide is pending. It provides control equivalent to methyl bromide for nematodes and the weed nutsedge.

The following is a summary of papers presented on the efficacy of methyl bromide alternatives for growing tomatoes.

3.1 MBAO Conference — 2001

- 3.1.1 Gilreath et al. (2001) reported on a three year study conducted in Florida comparing “standard methyl bromide soil fumigation to the best chemical alternative, a mixture of 1,3-dichloropropene (1,3-D) and chloropicrin used in combination with pebulate, and the best nonchemical alternative, soil solarization, for soilborne pest control and crop response in both fall tomatoes and spring double-cropped cucumbers over multiple years on the same site.” They found that “the most extra large and total marketable tomatoes were produced with methyl bromide and 1,3-D + chloropicrin + pebulate in 1998. There was no difference in tomato production among alternatives in 1999. During 2000, tomato production was comparable with methyl bromide and 1,3-D + chloropicrin + pebulate,

but solarization reduced yields to a level intermediate between that of the fumigants and the nontreated control.”

- 3.1.2 Locascio et al. (2001) studied different application methods of methyl bromide and its alternatives. They also compared high density polyethylene (PE) mulch versus virtually impermeable film (VIF) for weed control. They found that “fruit yields were highest with 1,3-D treatment applied broadcast with Pic and pebulate applied in the row, all MBr-Pic and methyl iodide Pic treatments, in row applied 1,3-D + 35% Pic at 196 L- ha⁻¹, and metam sodium applied with 3 drip lines. Fruit yields were significantly lower with broadcast applied 1,3-D + 35% Pic and broadcast metam sodium. Also, yields were significantly higher with PE than with VIF mulch.”
- 3.1.3 Chellemi et al. (2001) evaluated combinations of 1,3-dichloropropene (1,3-D) and chloropicrin along with the herbicides napropamide, pebulate, and trifluralin for the control of soilborne pests and their effects on marketable yield of tomato and pepper. They reported that “in tomato fields with a high incidence of Fusarium wilt and Fusarium crown rot, disease incidence in the alternative fumigant treatments ranged from 16% to 56% while disease incidence in methyl bromide treated areas averaged 18%. In tomato fields with high populations of the weed *Solanum nigrum* (black nightshade), none of the chemical alternatives provided acceptable weed control when compared to methyl bromide. In tomato fields where pest pressure was low to moderate, the fumigant/herbicide alternatives evaluated in the broadcast treatments provided levels of pest control similar to methyl bromide.” Napropamide is not registered yet for use on tomatoes.
- 3.1.4 Allan and Schiller (2001) report that, based on field trials, “efficacy studies have shown that Iodomethane provides equal to superior control of soil pests compared to methyl bromide with nearly identical spectrum of activity. Advantages include greater safety in handling since it is a liquid at room temperature, rapid photo degradation that eliminates the potential for ozone depletion, and lower overall use rates compared to methyl bromide. Use of conventional application equipment allows for an easier transition away from methyl bromide as it nears complete phase-out and for implementation of Iodomethane in its place.” Iodomethane is not registered for tomatoes.
- 3.1.5 Sances (2001) studied soil fumigation with several fumigants on strawberry, tomatoes, and floricultural crops, and found that Iodomethane alone and in combination with chloropicrin and Telone/chloropicrin were acceptable alternatives to methyl bromide. He also reported that, “these alternatives gave acceptable levels of control of soil pathogens, as well as producing yields equal to or better than methyl bromide/chloropicrin. Weed

control was good to excellent with Iodomethane.” Iodomethane is not registered for tomatoes.

- 3.1.6 Noling et al. (2001) examined alternatives to methyl bromide for controlling nematodes and nutsedge when growing tomatoes. “During fall 2000 and spring 2001, single preplant applications of Propargyl bromide (40-120 lb/A), Telone II (12 gal/A), Telone C17 (17 gal/A), Telone C35(26 gal/A), Propylene oxide (50,75 gal/A), Vapam (75 gal/A), and Basamid (400 lb/A) were evaluated for control of the southern root-knot nematode (*Meloidogyne incognita*) and yellow nutsedge (*Cyperus esculentus*), and resultant impacts on tomato plant growth, development, and yield in field microplots. Three biorational or new systemic acquired resistance compounds (SAR) also were evaluated and compared for nematode and nutsedge control. Biorational treatments included Armorex (30 gal/A) and repeated foliar applications of Messenger and Resist. . . . Use of Vapam and Basamid reduced root gall severity to only an intermediate level compared to the untreated control and most other fumigant treatments. Little or no reduction in root gall severity was achieved with Messenger, Resist, or Armorex. Of all the treatments, only Telone II, Messenger, and Resist failed to provide significant control of yellow nutsedge compared to the untreated control. . . . In general, all fumigant treatments significantly reduced root gall severity caused by *M. incognita* . . . ; however, no fumigant treatment completely eliminated final harvest root galling, and treatment responses in tomato yield were generally a direct reflection of nematicidal efficacy and root gall severity. . . .” Note that Propargyl bromide is not registered for use on tomatoes.
- 3.1.7 Adams et al. (2001) studied the efficacy of Plantpro 45, an iodine-based compound that “has indicated potential for control of root-knot and sting nematodes, some soilborne fungal and bacterial pathogens, seedborne fungal pathogens, and important weed species.” They found that “treatments with Plantpro 45 have resulted in yields comparable to methyl bromide in a number of tomato field trials. . . . A new formulation of Plantpro 20 EC, which is also a low-risk and more concentrated iodine-based compound similar to Plantpro 45, has also been shown to improve plant growth of field grown tomatoes when applied through drip irrigation.” Note that Plantpro 45 is not registered for use on tomatoes.

3.2 MBAO Conference — 2000

- 3.2.1 Locascio and Dickson (2000) reported the results of a multiyear study of methyl bromide and its alternatives. They found that “in spring 1999, tomato fruit yield (Table 1) with 1,3-D + 17% [pic], 1,3-D + 35% pic, and metam-Na [sodium] +1,3-D applied broadcast were statistically similar to that with in-row treatments of Mbr-Pic and 1,3-D + 35% pic.

. . . In spring 2000 (Table 2), tomato fruit yields with all fumigant treatments were statistically similar. . . . Application of 1,3-D + pic and metam sodium broadcast and then pressed into a bed provided pest control that was comparable to in-row 1,3-D or with MBr -Pic.”

- 3.2.2 Haglund (2000) spoke on behalf of the Metam Sodium Task Force and reported that “the efficacy of metam as a soil treatment for the control of soil borne pests such as nematodes, insects, diseases, weeds and weed seeds is well documented in the literature. The control achieved, as reported in the literature, is not always consistent and in some instances control has been marginal. Metam should not be considered a drop-in replacement for the combination of methyl bromide + chloropicrin. Because of the limited movement of metam in the vapor phase in the soil, standard shank injections are not always efficacious. . . . When metam is applied using a method combining soil incorporation and injection with a plastic tarp it is equivalent to standard methyl bromide + chloropicrin treatments for pest control in the surface 45 cm. of the soil profile.”
- 3.2.3 Eger (2000) reported on 35 tomato trials conducted between 1993 and 1999 to explore Telone products as alternatives to methyl bromide. In considering nematode, disease, and weed control as well as crop vigor, Telone products were as effective as methyl bromide products in most cases. As far as yield data, “Yields of tomatoes treated with Telone C-17 were 95% of those with MB/Pic and yields with Telone C-35 were over 103% of those with MB/Pic.”
- 3.2.4 Gilreath et al. (2000) reported on a study conducted in Florida comparing “standard methyl bromide soil fumigation to the best chemical alternative, a mixture of 1,3-dichloropropene (1,3-D) and chloropicrin used in combination with pebulate, and the best nonchemical alternative, soil solarization, for soilborne pest control and crop response in both fall tomatoes and spring double-cropped cucumbers over multiple years on the same site.” They found that “the most extra large and total marketable tomatoes were produced with methyl bromide and 1,3-D + chloropicrin + pebulate in 1998. There was no difference in tomato production among alternatives in 1999.” Note that in 2000 solarization was not as efficacious; see #1 in 2001.
- 3.2.5 Noling et al. (2000) found that “application rates of propargyl bromide as low as 40 lb/a provided equivalent tomato yield to that of most alternative fumigants and to the nematode free controls produced by the application of methyl bromide. . . . [However,] propargyl bromide application rates between 40 and 80 lbs/a was required to achieve effective control of yellow nutsedge.” Propargyl bromide is not registered for use on tomatoes.

- 3.2.6 Kokalis-Burelle et al. (2000) examined several reduced risk and biological alternatives to methyl bromide. They found that “Plantpro reduced parasitic nematode populations to levels comparable to that of methyl bromide in Lake Jem at 10 and 45 and 63 DAP while increasing numbers of nonparasitic nematodes at Lake Jem, Live Oak and Sanford test sites. This indicates that Plantpro had a minimal effect on the populations of beneficial soil microorganisms. Plantpro treatments were comparable to methyl bromide in controlling disease caused by root-knot nematodes at 21 DAP at Lake Jem. Total yield of tomato from Plantpro treated plots at the Sanford site was equivalent to that of methyl bromide treated plots. . . . Trials in Lake Jem and Live Oak are not yet available.” Plantpro is not registered for use on tomatoes.

3.3 MBAO Conference — 1999

- 3.3.1 Nelson et al. (1999) examined soil flooding and chemical alternatives for Florida tomatoes. They indicated that “marketable yields of tomatoes were statistically equivalent in methyl bromide, Telone C-17, and Telone C-35 treatments, resulting in significantly higher yields than both metam sodium+1,3-D+Peb and untreated treatments.”
- 3.3.2 Chellemi et al. (1999) at the University of Florida studied solarization. “The impact of 19 different soil disinfestation treatments on marketable yield, disease incidence and fungal colonization of root systems was studied on pepper and tomato. . . . Treatments were applied and the crops grown on either commercial production farms at an experiment station. . . . Marketable yields in alternative treatments ranged from 96% to 123% of yields obtained in methyl bromide fumigated soil. Yields in soils treated with a combination of soil solarization and biosolid compost declined slightly after the first year but increased after the second and third consecutive year of treatment. Deep disking prior to the application of soil solarization resulted in increased yields.”
- 3.3.3 McMillan and Bryan (1999) compared metam sodium and methyl bromide for their efficacy in controlling nematodes and effect on tomato yields. They found that “Metam sodium when applied at the 60 gallon per treated acre provides adequate control of soil-borne pest and reduces weed populations. . . . Metam sodium is still the only fumigant that can provide tomato growers with some degree of controlling the soil-borne problems that was easily taken care of by the application of methyl bromide (MC33).”
- 3.3.4 Noling and Gilreath (1999) reported: “In summary, propargyl bromide proved to be a compound which was easy to handle and apply, demonstrated excellent nematicidal and herbicidal activity, and produced tomato yields equal to that of methyl bromide. Field

research with propargyl bromide is continuing; however, other factors and regulatory concerns must be addressed before being realistically considered a potential alternative to methyl bromide.” Propargyl bromide is not registered for use on tomatoes.

Table 3. Alternatives to methyl bromide for use on tomatoes.

Alternative	Citation	Number in Section 3	Efficacy information
Basamid	Noling et al., 2001 (#14)	3.1.6	Lower yields than methyl bromide
Iodomethane (methyl iodide)	Allan and Schiller, 2001 (#5)	3.1.4	Comparable to or better than methyl bromide
	Sances, 2001 (#45)	3.1.5	Comparable to or better than methyl bromide
Iodomethane + chloropicrin	Locascio et al., 2001 (#17)	3.1.2	Comparable to methyl bromide
	Sances, 2001 (#45)	3.1.5	Comparable to or better than methyl bromide
Metam sodium	Locascio et al., 2001 (#17)	3.1.2	Applied broadcast — lower than methyl bromide; applied with 3 drip lines — comparable to methyl bromide
	McMillan and Bryan, 1999 (#91)	3.3.3	Adequate compared to methyl bromide
Metam sodium applied with soil incorporation and injection with plastic tarp	Haglund, 2000 (#49)	3.2.2	Comparable to methyl bromide
Napropamide (devrinol)	Chellemi et al., 2001 (#15)	3.1.3	Lower than methyl bromide in fields with high populations of the weed <i>Solanum nigrum</i> ; comparable to methyl bromide in fields with low to moderate pest pressure
Pebulate	Chellemi et al., 2001 (#15)	3.1.3	Lower than methyl bromide in fields with high populations of the weed <i>Solanum nigrum</i> ; comparable to methyl bromide in fields with low to moderate pest pressure
Plantpro 20 EC	Adams et al., 2001 (#26)	3.1.7	Comparable to methyl bromide

Table 3. Alternatives to methyl bromide for use on tomatoes (cont.).

Alternative	Citation	Number in Section 3	Efficacy information
Plantpro 45	Adams et al., 2001 (#26)	3.1.7	Comparable to methyl bromide
Propargyl bromide	Kokalis-Burelle et al., 2000 (#61)	3.2.6	Comparable to methyl bromide
	Noling et al., 2000 (#30)	3.2.5	Comparable to methyl bromide
Soil solarization	Noling and Gilreath, 1999 (#33)	3.3.4	Comparable to methyl bromide
	Chellemi et al., 1999 (#35)	3.3.2	Comparable or better
Telone + chloropicrin (Telone C35, Telone C17)	Gilreath et al., 2001 (#13)	3.1.1	Comparable to methyl bromide in first year, lower in third year
	Gilreath et al., 2000 (#41)	3.2.4	Comparable to methyl bromide
	Locascio et al., 2001 (#17)	3.1.2	Comparable to methyl bromide
	Chellemi et al., 2001 (#15)	3.1.3	Lower than methyl bromide in fields with high populations of the weed <i>Solanum nigrum</i> ; comparable to methyl bromide in fields with low to moderate pest pressure
	Sances, 2001 (#45)	3.1.5	Comparable to or better than methyl bromide
	Locascio and Dickson, 2000 (#42)	3.2.1	Comparable to methyl bromide
	Eger, 2000 (#40)	3.2.3	Telone C17 yield 95 % of methyl bromide; Telone C35 yield 103% of methyl bromide
	Nelson et al., 1999 (#13)	3.3.1	Comparable to methyl bromide
Telone + metam sodium (broadcast)	Locascio and Dickson, 2000 (#42)	3.2.1	Comparable to methyl bromide
Telone+ chloropicrin + pebulate	Gilreath et al., 2001 (#13)	3.1.1	Comparable to methyl bromide
	Locascio et al., 2001 (#17)	3.1.2	Comparable to methyl bromide
	Gilreath et al., 2000 (#41)	3.2.4	Comparable to methyl bromide
	Nelson et al., 1999 (#13)	3.3.1	Lower than methyl bromide

Table 3. Alternatives to methyl bromide for use on tomatoes (cont.).

Alternative	Citation	Number in Section 3	Efficacy information
Trifluralin	Chellemi et al., 2001 (#15)	3.1.3	Yields lower than methyl bromide in fields with high populations of the weed "Solanum nigrum"; yields comparable to methyl bromide in fields with low to moderate pest pressure

4. Tree Fruits and Nuts

One of the problems facing fruit and nut tree growers is that trees replanted in an orchard that previously had the same types of trees tend to grow slowly, mature later, and produce lower yields. This is referred to as "replant disorder," believed to result from a complex of major and minor soil-borne plant pests whose populations evolved with the previous orchard. Fumigation with methyl bromide reduces this replant disorder; and the new trees are more vigorous and uniform. It also keeps pests under control once the orchard is planted. California produces nearly all of the national production of almonds, clingstone peaches, dates, English walnuts, figs, kiwifruit, nectarines, olives, and pistachios (California Department of Food and Agriculture, 2000, p. 77). Almonds, peaches, and walnuts are the heaviest users of methyl bromide. These three commodities used about 3% of the methyl bromide used in California (California Department of Pesticide Regulation, 2001, pp. 227-230).

There have been eight studies about replanting orchards in the last three MBAO conferences. Growers anxious to replant at once have the option of using Telone and metam sodium, both of which control nematodes as well as methyl bromide. Micro-irrigation systems and the use of plastic mulch are also options that help reduce insect pests. Letting the land lie fallow for a year is another option, but Trout and Ajwa (2001) found that a year of fallow was not as efficacious as treatment with methyl bromide. Probably the most promising alternative not yet registered is methyl iodide, the subject of three studies. The following represent some of the papers on this issue presented at the MBAO conferences in recent years:

- 4.1.1 Trout et al. (2001) examined the effectiveness of fallowing and fumigation with Telone and chloropicrin as alternatives to methyl bromide to address "replant disorder" for peaches. They concluded that "increasing fallow periods reduce the replant disorder. One year gives some benefits, but even three years may not be sufficient to control the problem as well as methyl bromide. Fallowing is an expensive option for orchard crop

growers, especially for peaches that are replanted an average of every 7 years in California. Drip-applied Telone is effective against the replant problem. The dramatic growth response with chloropicrin fumigation merits further study. Work is needed to determine the etiology of the replant problem.”

- 4.1.2 Eayre and Sims (2000) compared methyl bromide and methyl iodide to address replant disorder for peach trees. They concluded that “methyl iodide fumigated plots did not differ from methyl bromide fumigated plots in trunk growth, weight of branch prunings, or reductions in population densities of the nematode *Paratylenchus*. Methyl iodide and methyl bromide appeared to be equally effective in controlling replant disorder.”
- 4.1.3 At the MBAO 2000, Trout (2000) said, “Since Telone was re-introduced in 1994, use of this product has increased dramatically for certain crops. As an effective nematicide, it is used mainly on root crops (carrot, sweet potato, potato) and for replant of perennial fruit and nut trees.”
- 4.1.4 Schneider et al. (2000) examined the use of methyl bromide and alternatives for grapevine replant. In the replant trials, “There were no detectable plant parasitic nematodes in any of the plots treated with methyl bromide (MB), methyl iodide (MI), or the Telone/vapam (T/V) combinations until April 2000, and then only at extremely low levels. . . . The Telone/vapam combinations and methyl iodide have controlled the nematode populations as well as methyl bromide to date. . . . The use of rootknot resistant rootstocks reduced the population level of rootknot, but not citrus, nematodes.”
- 4.1.5 Stapleton and Duncan (1999) reported on a long-term field experiment “done during 1992-1997 to test effects of establishing apricot (*Prunus armeniaca* L. cv. Patterson on apricot rootstock) trees with black polyethylene mulching under the semi-arid conditions of California’s San Joaquin Valley. . . . Black polyethylene film mulch was effective in controlling *Verticillium* wilt, increasing apricot fruit yields, and conserving soil moisture.” The experiment was conducted in anticipation of the methyl bromide ban.
- 4.1.6 Schneider et al. (1999) examined alternatives to methyl bromide for replanting grape vines. They found that “the Telone/vapam combinations and methyl iodide have controlled the nematode populations as well as methyl bromide to date. . . . In the short term, novel applications of currently available chemicals appear to be the most likely alternatives to methyl bromide. These will serve as stepping stones during the transition to an integrated systems management approach based on an understanding of the interactions and spatial variability of biological, chemical, and physical factors in the agro-ecosystem. Such a system will include cultural, genetic, biological, and chemical management strategies to reduce or eliminate pests, enhance beneficial organisms,

promote good plant growth, kill old roots deep in the soil that serve as pest reservoirs, and protect the environment.”

- 4.1.7 Trout and Ajwa (1999a) evaluated the use of micro-irrigation systems as a novel way to apply pesticides in replanted peach orchards. They found that “first year results on the 1997 and 1998 application to peaches show a significant increase in peach tree growth compared to non-fumigated (even though no plant parasitic nematodes were found in the field). Initial growth was less than the MeBr treatment, (likely due to early phytotoxicity), but second year growth appears to be comparable. The treatment also resulted in the reduction of the pin nematodes below detectable levels to a depth of 1.5 m. No other nematodes were detected in the fields.”

Table 4. Alternatives to methyl bromide for use on tree fruits and nuts.

Alternative	Citation	Number in Section 4	Efficacy information
Black polyethylene film mulch	Stapleton and Duncan, 1999 (#22)	4.1.5	Effective control of verticillium wilt and increased yields in apricot trees in semi arid conditions
Fallowing	Trout, 2001 (#23)	4.1.1	Not as effective as methyl bromide for peach tree replant
Methyl iodide	Eayre and Sims, 2000 (#95)	4.1.2	Comparable to methyl bromide for peach tree replant
	Schneider et al., 2000 (#14)	4.1.4	Comparable nematode control
	Schneider et al., 1999 (#50)	4.1.6	Comparable to methyl bromide for nematode population control in grape replant
Micro-irrigation systems	Trout and Ajwa, 1999a (#44)	4.1.7	Initial growth of peach tree replant lower than methyl bromide, but second year comparable
Telone	Trout et al., 2001 (#23)	4.1.1	Drip applied effective for peach tree replant
	Trout, 2000 (#105)	4.1.3	Effective nematode control
Telone + vapam (metam sodium)	Schneider et al., 2000 (#14)	4.1.4	Comparable nematode control
	Schneider et al., 1999 (#50)	4.1.6	Comparable to methyl bromide for controlling nematodes in grape replant

5. Forest, Sod, Ornamentals, and Nurseries

Forest nurseries, sod farms, ornamental growers, and other nurseries use methyl bromide as an effective soil fumigant. In all, this grouping includes 13 studies in the past three years of MBAO conferences (Table A.4 in the appendix), and includes forest nurseries, about which there have been two studies, grapevine nurseries, the subject of one study, ornamentals and flowers the subject of four studies, and strawberry nurseries the subject of six studies.

A problem for all nursery growers in California, such as strawberry nurseries, is that for on-farm use (Carpenter, 2000, p. 190) the stock must be free of nematodes. It can be certified by either using an approved treatment, namely methyl bromide or 1-3,D (the active ingredient in Telone), or by field sampling just before harvest. It is more practical to do the former, since the latter results in the entire crop being lost if nematodes are detected. The registered alternatives to methyl bromide are basamid, chloropicrin, metam sodium, and Telone. The most promising alternative not yet registered is methyl iodide. Basamid (dazomet) was the subject of one study of nursery growers' attitudes toward it: three growers said that it is efficacious, two said it was not. Chloropicrin alone or in combination with other substances was tested in six studies; in all of them it was comparable to methyl bromide. Metam sodium alone or in combination with other alternatives is also comparable to methyl bromide. Telone is also efficacious; in every study the yields were comparable to those achieved with methyl bromide. Unregistered alternatives tested are propargyl bromide and methyl iodide, both of which give yields comparable to those achieved with methyl bromide.

5.1 Alternatives for Multiple Crops

- 5.1.1 Sauerhoff (1998) reported that "in California, because of the low cost, ease of application, safety, and effectiveness in controlling soil pests, over 15 million pounds of metam sodium were used in the production of melons, peppers, tomatoes, potatoes, strawberries, nurseries, ornamentals, cut flowers, container plants, forest tree seedlings, citrus, grapes, almonds, artichokes, asparagus, and carrots. Metam sodium reduces competition from soil pests, promotes healthier crops and higher yields, provides early uniform crop maturity and fruit ripening, and allows growers to greatly increase economic returns by achieving maximum early season yields."
- 5.1.2 Porter (1999) reports that "since 1992, a range of chemical and non-chemical soil disinfestation options to MB have been evaluated in randomised block trials in the strawberry fruit and runner industries, and the tomato and ornamental flower bulb industries in Victoria and Queensland. From this work, the most likely alternatives have

been evaluated over the past two seasons in grower demonstration trials on growers properties at 6 sites throughout Australia. Generally chemical treatments have included alternative fumigants or mixtures of MB, chloropicrin (Pic), 1,3-dichloropropene (1,3-D), metham sodium (MS) and dazomet. The non-chemical treatments have included, solarisation either alone or in combination with fumigants, hot water, biological controls (e.g., Nemacheck . . .), biofumigants, herbicides and pesticides, and a range of nutrient treatments (calcium cyanamide, calcium oxide). In the flower bulb industry to date, three alternative chemical fumigants (Pic, MS/Pic and 1,3-D/Pic) have been as effective as MB for control of *Sclerotium rolfsii*, and clearly more effective than other treatments. In the strawberry industry, similar results have been obtained and mixtures of MB/Pic with lower concentrations of methyl bromide (30:70) have consistently outyielded (up to 14% greater) crops treated with the standard MB/Pic mixture (70:30). . . . Supplementary programs, such as the use of fungicide dips and disease free bulbs are reducing the need for flower growers to annually fumigate soils for flower bulb crops. Alternative fumigants together with herbicide programs have shown promise for replacing the need for MB fumigation in the strawberry runner industry, however, the need for certification of runners, is forcing this industry to consider other production strategies (e.g., Soilless culture and protected cropping).”

5.2 Forest Nurseries

- 5.2.1 James et al. (2001) reported on a project, started in 1990, in which five USDA nurseries evaluated methyl bromide and dazomet. At an Idaho nursery, dazomet fumigation was the current treatment of choice and fallowing with supplemental additions of biocontrol agents and steam treatments were considered possible satisfactory alternatives. A second nursery in Idaho found that fallowing and dazomet fumigation were not effective, and an efficacious alternative to methyl bromide chloropicrin was not yet available. Two nurseries, in Oregon and California, found dazomet to be a viable alternative. The fifth nursery, in Nebraska, considered methyl bromide as the treatment of choice primarily due to its effectiveness against soil nematodes.
- 5.2.2 The Auburn University Southern Forest Nursery Management Cooperative conducted trials to evaluate many of the registered soil fumigants and combinations of fumigants. Carey (2000) reported on the trials and noted that “at the Flint River Nursery in 1997 and at trials near Glenville, GA. and near Beauregard, LA in 1998 (Carey, 2000) combinations of chloropicrin plus metham sodium (CMS) produced pine seedlings as well as plots fumigated with methyl bromide (Mbr). . . . However, since tarping normally increases fumigation efficacy and should increase safety we compared our previously tested rate of CMS (250 lbs of chloropicrin plus 250 lbs of metham sodium per acre) with

a tarped application in which the chloropicrin was reduced an amount (100 lbs/ac) estimated to approximately equal the cost of the tarp. . . . Mean numbers and sizes of seedlings did not differ at either nursery or for the combined analysis of both nurseries. . . . Questions about the efficacy of tarping CMS applications became more important after this study was implemented when seedlings in beds around non-tarped CMS applications in Louisiana and in Texas were damaged. The equivalent efficacy of the tarped CMS application is good news in efforts to find a safe alternative to MBr. However, cost effective utilization requires equipment that can apply and tarp the CMS in one pass.”

5.3 Grapevine Nurseries

- 5.3.1 Schneider et al. (2000) examined the use of methyl bromide and its alternatives for grapevine nurseries. The nursery treatments they studied were methyl bromide at 400 lb/acre (treated control), tarped; shanked methyl iodide (200 lb/acre)+chloropicrin (200 lb/acre), tarped; drip applied Telone II EC (44 gal/acre or 390 lb/acre of 1,3-D), tarped; drip applied methyl iodide (200 lb/acre)+chloropicrin (200 lb/acre), tarped; drip applied methyl iodide (100 lb/acre)+chloropicrin (100 lb/acre), tarped; drip applied propargyl bromide - (100 lb/acre), tarped; drip applied propargyl bromide (200 lb/acre), tarped. They found that “no live nematodes were recovered at any depth in the shanked treatments. All dripped treatments gave excellent control at the 1 ft. depth. At the 3 ft. level, fewer than 5 nematodes were recovered in the high rate of propargyl bromide and both rates of methyl iodide/chloropicrin compared to 160 nematodes in the untreated control. Effective control at the 5 ft. level was achieved only with the low and high rates of methyl iodide/chloropicrin.”

5.4 Ornamentals and Flowers

- 5.4.1 Elmore et al. (2000) examined the use of solarization with and without the use of plant extracts, such as broccoli, to control weeds. Field trials were conducted with calla lilies, godetia, and snapdragons in three studies. In the first study they found that “soil solarization controlled greater than 90% of all weeds at 5 cm depth at Davis in the pot tests. Incorporation of broccoli in the top 2 or 6 inches of soil followed by tarping controlled more than 95% of all weeds at 5 cm after 2 weeks of treatment. Though broccoli residue plus solarization decreased weed seed germination at 15 and 30 cm, it was not as effective as metham as a standard treatment which gave complete control to 30cm depth. Similar results were obtained with pathogens and citrus nematode. . . .” In the second study they determined that “at the coastal site 5 dry tons of broccoli reduced

the number of calla lily regrowing from rhizomes by 66% without significantly increasing soil temperature. Weeds were reduced with the combination of broccoli incorporated followed with soil solarization for 6 weeks.” And in the third study, they found that “in the Davis field site, rough pigweed, common purslane and annual bluegrass were controlled with the soil solarization treatments or with 35 T wet broccoli biomass either spaded into the top 5 cm of soil or rototilled into the top 13 cm of soil and covered with clear tarp for 6 weeks.”

- 5.4.2 Elmore (1999) examined soil solarization for weeds and soil-borne pathogens for cut flowers in field trials. He found that “although weed control with soil solarization can be improved with chemical additives or organic additives, the combinations have not been as effective for broad-spectrum pest control as methyl bromide.”
- 5.4.3 Gilreath et al. (1999) evaluated several alternatives to methyl bromide in the growing of caladium tubers, in the ornamental category. “Fumigant treatments evaluated consisted of 1) no fumigant; 2) methyl bromide / chloropicrin (90/10 %) at 450 lbs./acre; 3) 1,3-dichloropropene (1,3-D) / chloropicrin (83/17%) (Telone C-17) at 35 gal./acre; and 4) 75 gal. of metham (Sectagon) per acre + 200 lbs. of chloropicrin (pic) per acre. Metolachlor herbicide (8 lbs./acre) was applied at planting to plots treated with 1,3-D or metham. . . . There was no difference in tuber production for any size grade, except jumbo, where significantly more tubers were produced in plots treated with 1,3-D + chloropicrin with metolachlor at planting followed by oryzalin in mid summer (Table 5). Chloropicrin + 1,3-D out produced all other fumigants for jumbos and there were no differences in jumbo production between methyl bromide or metham + chloropicrin or where no fumigant or herbicide was applied.”

5.5 Strawberry Nurseries

- 5.5.1 In California, research over a number of years has been devoted to the problems of strawberry nurseries. Fennimore et al. (2001a) presented a paper evaluating iodomethane for nursery production. They found that “for both a high elevation nursery and a low elevation nursery the effects of IM/Pic [iodomethane/chloropicrin] at 350 lb/A and MB/pic at 400 lb/A were equivalent in reducing common chickweed, common purslane, prostrate knotweed and strawberry seed. . . . None of the fumigants were active on little mallow.”
- 5.5.2 Fennimore et al. (2001b) reported that “alternative fumigants such as chloropicrin, 1,3-D plus chloropicrin mixture, dazomet and iodomethane have been evaluated in strawberry nurseries. . . . Thus far the results suggest that iodomethane plus chloropicrin in

50:50 mixture is a viable alternative fumigant for strawberry nurseries, since plant health is comparable to plants produced with methyl bromide plus chloropicrin 57:43.”

- 5.5.3 Research results indicate that plug plants are preferable to bare-rooted plants but are more expensive. Sances (2001) reported that “alternative strawberry plug plant research this season was established at the Pacific Ag Research coastal farm in San Luis Obispo, and in several grower cooperator fields in Oxnard and Irvine California. . . . At all the sites, plug plants were compared to bare root plants for production and overall plant performance. . . . In all cases, plug plants outperformed bare root transplants by significant margins until the first of March. . . . Depending on the individual site, the plug plant system yielded two to three weeks earlier than bare root plantings. This period corresponded to higher market price conditions for growers.”
- 5.5.4 Fennimore et al. (2000) also reported, on iodomethane as an alternative for methyl bromide in strawberry nurseries, that “the weed control efficacy of iodomethane/chloropicrin 50:50 was approximately equal to methyl bromide.”
- 5.5.5 Sances (2000) reported that “among all inputs tested, the use of plug plants for strawberries had the greatest effect on yield. In each soil management system, the resulting fruit production was markedly higher than the bare-root transplants. The fruit was also of equal quality with respect to deformities and other defects. It should be noted, however, that the cost of this technology is much higher than bare root plants. At current prices, plug plants sell for more than three-fold that of bare roots of the same cultivar. The true cost of the technology, however, is the benefit derived from the earlier and higher yields obtained, minus the difference in direct cost of the plug plants.”

5.6 Sod

- 5.6.1 Lindberg and McKeague (2001) presented a case study about a Canadian sod nursery and explained that “[this nursery] stopped using methyl bromide in 1994-1995. Now crops are rotated on a three-year cycle (nursery crop, rotation crop, green manure crop.) . . . [In the fall of the second year] 1,3-dichloropropene is applied. . . . Two to three weeks after treatment, a winter cover crop (rye or wheat) is directly drilled into the soil. In the spring they kill the cover crop with glyphosate and then harrow the fields and plant nursery stock again.”

Table 5. Alternatives to methyl bromide for use on forest, sod, ornamentals, and nurseries.

Alternative	Citation	Number in Section 5	Efficacy information
Chloropicrin	Porter, 1999 (#17)	5.5.4	Comparable to methyl bromide
Crop rotation and Telone	Lindberg and McKeague, 2001 (#134)	5.6.1	Comparable to methyl bromide
Dazomet (Basamid)	James et al., 2001 (#78)	5.2.1	3 out of 5 nurseries consider dazomet a viable alternative to methyl bromide, 2 do not feel it is as effective.
Metam sodium	Sauerhoff, 1998 (#29)	5.1.1	Effective in controlling soil pests
Metam sodium + chloropicrin	Porter, 1999 (#17)	5.1.2	Comparable to methyl bromide
	Gilreath et al., 1999 (#16)	5.4.3	Comparable to methyl bromide
Iodomethane + chloropicrin (methyl iodide)	Schneider et al., 2000 (#14)	5.3.1	Comparable to methyl bromide
	Fennimore et al., 2000 (#65)	5.5.4	Comparable to methyl bromide
	Fennimore et al., 2001a (#39)	5.5.1	Comparable to methyl bromide
	Fennimore et al., 2001b (#96)	5.5.2	Comparable to methyl bromide
Tarped metam sodium + chloropicrin	Carey, 2000 (#51)	5.2.2	Comparable to methyl bromide
Plug plants (instead of bare roots)	Sances, 2001 (#45)	5.5.3	Comparable to methyl bromide
Plug plants	Sances, 2000 (#24)	5.5.5	Yield higher with plug plants than bare-root transplants
Propargyl bromide (drip applied, tarped)	Schneider et al., 2000 (#14)	5.3.1	Comparable to methyl bromide
Telone + chloropicrin	Porter, 1999 (#17)	5.1.2	Comparable to methyl bromide
	Gilreath et al., 1999 (#16)	5.4.3	Comparable to methyl bromide
Telone II EC (drip applied, tarped)	Schneider et al., 2000 (#14)	5.3.1	Comparable to methyl bromide
Soil solarization	Elmore et al., 2000 (#96)	5.4.1	Not as effective as metam sodium
	Elmore, 1999 (#48)	5.4.2	Not as effective as methyl bromide

6. Post-Harvest Uses

Methyl bromide is an effective fumigant for post-harvest storage and processing of agricultural products. Most of the research into alternatives has focused on heat treatments, cold treatments, carbon dioxide, vacuumed storage, low-pressure treatments, microwaving, and use of chemical substances like propylene oxide, phosphine, sulfuryl fluoride, pheromones, and methyl iodide. In the 1999-2001 MBAO conferences, heat and cold were the subject of nine studies, pheromones were the subject of one study, vacuum treatments were explored in three studies, and chemical alternatives were the subject of five studies, including two studies on sulfuryl fluoride, both of which concluded that it was a viable alternative to methyl bromide. Registration of sulfuryl fluoride is pending in the United States. Summaries of the research presented in the articles on these alternatives are presented below.

6.1 Heat and Cold Treatments

- 6.1.1 A multidisciplinary (engineering, entomology, and fruit physiology) team of university and USDA scientists (Wang et al., 2001) from Washington, California, and Texas examined “effective thermal treatment protocols using electromagnetic energy especially in radio frequency (RF) range in combination with conventional thermal methods such as water or air heating to achieve a delicate balance between minimized thermal impact on product quality and complete kill of insect pests. . . . Walnuts in the shell were treated with RF energy in a 27 MHZ pilot-scale system to determine the treatment effect on codling moth mortality and walnut quality. . . . After 2 and 3 min of RF treatments, infested in-shell walnuts were heated to 43 and 53°C. The corresponding insect mortality reached 78.6 and 100%. . . . RF treatments can, therefore, potentially provide an effective and rapid quarantine security protocol against codling moth in walnuts as an alternative to methyl bromide fumigation.”
- 6.1.2 Halverson et al. (2001) studied the use of microwave technology and reported that “recent tests of infested, freely flowing, hard red wheat, in a 28GHz microwave applicator indicate that a bounding energy input of 56.8 J/g will produce a mortality of 99% for the least vulnerable species and age level of each of the three major grain pests tested, i.e. hard red wheat, *Triticum aestivum* (L.), infested with pupae, young larvae and eggs of the rice weevil *Sitophilus oryzae* (L), the red flour beetle *Tribolium castaneum* (Herbst), and the lesser grain borer *Rhizopertha dominica* (F.).”

- 6.1.3 Phillips et al. (2001a) studied the use of microwave radiation for wheat and reported that “experiments by our group using microwaves at 28GHz determined mortality of three life stages of three species each of stored-product beetles to a range of power levels applied to insects in 200 g flowing wheat samples. The energy required to achieve 99% mortality of the most tolerant life stage (eggs of lesser grain borer or larvae of red flour beetles) was approximately 55 J/g with an upper 95% confidence interval of 75 J/g. Slight but significant effects of microwaves on grain quality were detected. However, values for percent germination (90-95%), flour yield (63%), percent protein (11.1%), dough mixing time (6-7 min), and bread baking quality (crumb texture of 9.8 and crumb grain of 9.5) were all within acceptable market values for grain treated at the highest microwave levels.”
- 6.1.4 Phillips et al. (2001b) examined the use of low pressure and heat treatment to control insects in post-harvest storage. They determined the “shortest exposures times estimated to elicit 99% mortality. . . . [They concluded that] practical applications of the vacuum method should be performed above 22.5C at pressures lower than 100 mm Hg for periods of at least 72 h. Successful pilot-scale applications were conducted in commercial settings with bag stacks of cocoa and coffee using flexible PVC hermetic storage structures.”
- 6.1.5 Johnson et al. (2001) discussed methyl bromide alternatives for dried fruit and tree nuts. They examined heat treatments using “a heating block system developed at Washington State University, Pullman WA, to study thermal tolerance of navel orangeworm and Indianmeal moth at heating rates comparable to those found in RF [industrial radio frequency] or microwave heating. . . . Using heating rates comparable to those obtained with RF or microwave heating, we obtained high mortality levels for the most thermal tolerant species, navel orangeworm, after relatively short exposure times (1 minute or less at 120.2°F). In addition to allowing treatment of large volumes of commodity, such rapid heat treatments may also avoid product damage in heat sensitive commodities. Preliminary quality studies with walnuts treated with RF energy for 3 minutes showed no significant increase in peroxide values or fatty acid levels.”
- 6.1.6 Halverson et al. (2000) studied the use of microwave technology and reported that “recent tests of infested, freely flowing, hard red wheat, in a 28GHz microwave applicator indicate that a bounding energy input of 56.8 J/g will produce a mortality of 99% for the least vulnerable species and age level of each of the three major grain pests tested, i.e. hard red wheat, *Triticum aestivum* (L.), infested with pupae, young larvae and eggs of the rice weevil *Sitophilus oryzae* (L.), the red flour beetle *Tribolium castaneum* (Herbst), and the lesser grain borer *Rhizopertha dominica* (F.)”

- 6.1.7 Johnson and Valero (2000) reported, on the use of cold storage, that “cowpea weevil may be easily controlled by temperatures found in commercial freezers. With rapid cooling rates, exposures of 6-24 hours reduced pest numbers by more than 99%.”
- 6.1.8 Menon and Subramanyam (2000) examined thermal disinfestation and determined that “a temperature of 50°C for a minimum of 3 hours kills all exposed life stages of *T. castaneum*. Sanitation is critical for removing refugia for insects and for effective insect management, because grain and flour residues act as heat insulators. Heat appears to be an appealing and safe alternative to methyl bromide. However, more quantitative information is needed on responses of other stored-product insects to heat and on the economics of using this technology. Such information would make heat more widely accepted and adopted by the food industry.”
- 6.1.9 Johnson and Valero (1999) studied cold storage to treat dried fruit and nuts and found that “relatively short-term low temperature storage of product containing only pyralid eggs would provide sufficient control. The storage durations needed to obtain 95% mortality decrease with temperature, and are unaffected by relative humidity. Suitable storage times for 10, 5 and 0°C were 12, 10 and 8 days, respectively. Exposure to low temperatures may be a practical means to disinfest relatively clean product briefly exposed to moths. Cold storage shows promise in combination with disinfestation methods such as controlled atmosphere treatments or high temperature dehydration procedures. Cold storage may also be used after treatments to which pyralid eggs are more tolerant, such as sulfuryl fluoride.”
- 6.1.10 Simpson et al. (2001) conducted research to develop an alternative disinfestation treatment for harvested chrysanthemum cuttings. They reported that “the key pests of field grown chrysanthemums are melon aphid (*Aphis gossypii* Glover), silverleaf whitefly (*Bemisia argentifolii*), and the agromyzid leafminer, *Liriomyza trifolii* (Burgess). In addition, two-spotted spider mites (*Tetranychus urticae* Koch) and western flower thrips [*Frankliniella occidentalis* (Pergande)] can be incidental pests. We are currently testing various temperatures and exposure times in an effort to develop a heat treatment which can control all lifestages of these pests. . . . Temperatures tested ranged from 118°F (48°C) to 126°F (52°C) with exposure times from 20 to 120 minutes Melon aphids and western flower thrips were completely controlled at temperatures and exposure times well within the tolerance of mum cuttings. Two-spotted spider mites are more resistant to the treatments, with mortality well below that of the other pests tested (data not shown). Preliminary data indicates that adult whiteflies and leafminers can be controlled by forced hot air, however, the immature stages could be more resistant to the treatments. . . . Further work is needed to explore the effects of temperature and exposure time on the various lifestages of these target pests.”

6.2 Pheromones

- 6.2.1 Mating disruption with the use of pheromone baited traps was studied by Burksa et al. (2001) for the control of Indianmeal moth in warehouses. While the authors report the efficacy of such a method, there is no comparison drawn between this and the use of methyl bromide.

6.3 Vacuum Treatments

- 6.3.1 Villers (2001) reported, on a pesticide-free vacuum fumigation technique, that “the team has done so using flexible structures for modified atmosphere-hermetic storage, as well as hermetic storage with unmodified atmospheres. Modified atmosphere applications include vacuum-hermetic fumigation (V-HF), which involves sealing commodities in a hermetic enclosure, and drawing a vacuum down to 35 mm Hg, and CO₂-hermetic fumigation, which involves applying 99% CO₂ to commodities in hermetic enclosures. In the novel context of flexible hermetic storage structures made of strong, lightweight UV-resistant PVC, laboratory and field data confirm that both processes at room temperatures typically kill relevant insect pests within three days. To date, laboratory and field tests have been performed on cocoa, coffee, and dates, with experiments planned for nuts, other dried fruit, and spices.”
- 6.3.2 Simcha et al. (2001) studied the use of vacuum-hermetic technology and reported that “the effects of low pressures and exposure time were studied on the mortality of insects at a temperature of 18°C, chosen to simulate cacao bean storage conditions in temperate climates. Three insects were used, two of which are major pests of cacao beans in producer countries: *Ephestia cautella* (Walk.), and *Tribolium castaneum* (Herbst), while the third, *Oryzaephilus surinamensis* (L.), is a potential storage pest in the destination countries. For *T. castaneum* and *E. cautella* the egg stage was the most resistant to 55 ± 10 mm Hg at 18°C, the times needed to obtain egg mortality of 99% was 96 and 149 hours respectively. For *O. surinamensis*, the adult stage was the most resistant with 164 hours being required to obtain 99% mortality.”
- 6.3.3 Navarro et al. (2001) attempted to “identify the combinations that enhance the effectiveness of the treatments based on vacuum or a combination of heat and CO₂. Experiments were carried out using a 15-m³ capacity plastic container termed the ‘Volcani Cube’ or ‘GrainPro Cocoon.’ The pressure was maintained between 25 to 29 mm Hg for 17 days. . . . Bioassays in field trials were conducted with 7 tonnes of cocoa beans stored in the ‘Volcani Cube.’ These trials demonstrated that complete mortality of test insects composed of mixed ages of *E. cautella*, and *T. castaneum* was

observed on the 3-days exposure to low pressures maintained within the range of .22 and 75 mm Hg.”

6.4 Chemical Alternatives

- 6.4.1 Isikber et al. (2001) reported that “propylene oxide (PPO) is an FDA approved fumigant to control microbial contamination in dry and shelled walnuts. . . . The results obtained from this study suggest that the combination of propylene oxide with CO₂ or vacuum can be a potential as fumigant for replacing Methyl Bromide in some critical applications. However, further research is needed to obtain data on its absorption by different commodities and its penetration through the mass of commodities.”
- 6.4.2 Wontner-Smith et al. (2001) studied alternatives to methyl bromide for stored wheat in Syria and reported that “a UNIDO funded project was undertaken to demonstrate that carbon dioxide (CO₂) or phosphine, supplied from a conventional solid formulation or from a cylinder-based source of 2% phosphine, offered viable alternatives to the use of MB in terms of efficacy, safety and cost. . . . It proved impractical to dose the outdoor stacks with CO₂ because of wind but good results were obtained indoors. . . . The trials successfully demonstrated that phosphine in particular could be used as a safe alternative to MB within stores, or outdoors if sheltered from the wind, for treatment of bagged wheat.”
- 6.4.3 Aung et al. (2001) tested methyl iodide “at 10-60 mg/liter and found rates > 25 mg/liter efficacious against California red scale on lemons and codling moth eggs of nectarine, but these results were accompanied by significant fruit injury. . . . Work is continuing with determining the effects of MI and post-aeration on several major commodities to establish efficacy and degrees of phytotoxicity.”
- 6.4.4 Bell and Drinkall (2000) studied sulfuryl fluoride (SF) as an alternative to methyl bromide for use on certain commodities and in structures such as flour mills. They reported that “pupae and larvae of *E. kuehniella* and *T. castaneum* were all killed by concentration x time products (CTP) lower than 100 mg.h/l at 25 and 30°. In contrast, eggs of these species and those of *T. variable* required substantially higher dose levels for control. Increasing temperature from 20 to 30°C greatly increased the efficacy of SF, enabling CTP’s to be reduced by a factor of approximately 5-fold, depending on the species. Insect development, temperature, concentration thresholds for effective action and length of exposure time control the results obtained. CTP’s effective against the egg stage of stored product insects have been achieved in recent trial fumigations of flour

mills. From these results and those obtained on insect eggs, it can be concluded that SF fumigation of flour mills offers a viable alternative to fumigation with MB.”

- 6.4.5 Williams and Schnieder (1999) examined the fumigation of food processing plants and reported that “both methyl bromide and phosphine are used currently, although methyl bromide is generally favored due to its shorter exposure times and to its greater safety to electronic equipment. Interest in the use of sulfuryl fluoride (a widely-used structural fumigant for termites and other wood-destroying insects for over 30 years) as an alternative to current fumigants has lead to a number of FPP field trials to confirm stored-product insect pest (SPIP) efficacy and to develop necessary labeling. . . . Results from these six fumigation field trials confirmed many expectations, suggesting that: Sulfuryl fluoride is an effective alternative to methyl bromide for 24-48 h fumigations for stored-product insect pests in food processing plants.”

Table 6. Alternatives to methyl bromide for post harvest uses.

Alternative	Citation	Number in Section 6	Efficacy information
Carbon dioxide (CO ₂)	Wontner-Smith et al., 2001 (#71)	6.4.2	Viable alternative to methyl bromide for indoor applications (impractical for outdoor)
Cold storage	Johnson and Valero, 2000 (#90)	6.1.7	99% pest mortality with commercial freezers, rapid cooling rates and 6-24 hour exposure
	Johnson and Valero, 1999 (#65)	6.1.9	Effective for pyralid eggs and moths
Heat treatments	Johnson et al., 2001 (#60)	6.1.5	High mortality levels for the most thermally tolerant pests
	Menon and Subramanyam, 2000 (#91)	6.1.8	50°C for 3 hours kills all exposed life stages of T. castaneum
	Simpson et al., 2001 (#117)	6.1.10	Harvested chrysanthemum cuttings can tolerate heat treatments to kill pests
	Wang et al., 2001 (#82)	6.1.1	RF treatments kill pests on walnuts in shell

Table 6. Alternatives to methyl bromide for post harvest uses (cont.).

Alternative	Citation	Number in Section 6	Efficacy information
Vacuum hermetic fumigation (exposure to low pressure)	Villers, 2001 (#65)	6.3.1	Typically kill relevant pests within a few days
	Navarro et al., 2001 (#68)	6.3.3	Complete mortality of test insects after 3 days
	Simcha et al., 2001 (#69)	6.3.2	99% mortality of most resistant pests after 164 hours (7 days)
Heat with vacuum	Phillips et al., 2001b (#122)	6.1.4	99% mortality at temperature of 22.5°C and pressure lower than 100 mm Hg for at least 72 hours
Methyl iodide	Aung et al., 2001 (#123)	6.4.3	Significant fruit injury
Microwave applicator (28GHz)	Halverson et al., 2001 (#83)	6.1.2	56.8 J/g produces 99% mortality of least vulnerable pests
	Halverson et al., 2000 (#89)	6.1.6	56.8 J/g produces 99% mortality of least vulnerable pests
	Phillips et al., 2001a (#121)	6.1.3	55 J/g produces 99% mortality of most tolerant lifestage, slight but significant effects on quality of grain.
Pheromones	Burska et al., 2001 (#63)	6.2.1	Efficacious for Indian meal moths
Phosphine	Wontner-Smith et al., 2001 (#71)	6.4.2	Viable alternative to methyl bromide for indoor applications (impractical for outdoor)
Propylene oxide (PPO) with CO ₂ or vacuum	Isikber et al., 2001 (#70)	6.4.1	Potential replacement for methyl bromide in some critical applications
Sulfuryl fluoride (SF)	Bell and Drinkall, 2000 (#75)	6.4.4	Viable alternative to methyl bromide
	Williams and Schneider, 1999 (#63)	6.4.5	Effective alternative to methyl bromide

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Appendix. Telone Township Caps in California

Telone appears to be an effective alternative to methyl bromide for strawberries in California, tomatoes in certain areas of Florida, and various other crops. However, since Telone is a hazardous air pollutant and a ground water contaminant, the California Department of Pesticide Regulation (CaDPR) has set limits on how much Telone can be used in each township. CaDPR does not allocate Telone to individual growers. Instead, Dow AgroSciences, a division of the Dow Chemical Company, is responsible for allocating their product in each township.

Carpenter and Lynch (1999) summarized the restrictions as follows: “The limit on the amount of 1,3-D that may be used in each township depends on application depth and timing of applications within each township. A total of 90,250 lbs of 1,3-D per township is allowed if all applications are made to a depth of greater than 18 inches between February and November. The limit is lower if applications are made at shallow depths or during December or January.” They indicate that each pound applied at shallower depths is counted at a ratio of 1.9:1.

In 1997, 40% of Telone use was for carrots, with potatoes, including sweet potatoes, being the next largest single crop use, and perennial crops, including grapes, almonds and walnuts, also accounting for a substantial proportion of use (Carpenter and Lynch, 1999). As a result of the methyl bromide phase-out, likely crops to switch to Telone include strawberries, strawberry nurseries, various other vegetable crops, and perennials.

In 2001, CaDPR agreed to a temporary relaxation of township caps in some townships in Merced and Kern counties; each township was allowed to “bank” allocations not used during the previous 5 years. The townships could then draw on these banked amounts, up to twice the township cap of 90,250 lb. CaDPR also agreed to count drip irrigation at 1.6:1 pound (personal communication, Joe Busacca, Dow AgroSciences, 10/17/02). In early 2002 CaDPR raised the statewide township caps to about 180,000 lb “on an interim basis” (e-mail from T. Jones, CaDPR, 10/18/02).

Timing of use is also an issue with caps. If the caps are exceeded early in the year when most crops are planted, there will be no allocation available for growers who want to use it later. Dow’s allocation process does not appear to address this problem. The rule for 2003 is that shank-injected Telone can be requested no more than 7 days in advance; drip-injected uses, because of the time needed to prepare the beds, can be requested 45 days in advance. Dow may base the allocation on acreage requested or may use a lottery with chances based on acreage when requests exceed township caps; for example, each grower would be given one chance for each 20 acres requested (personal communication, Debbie Shatley, Dow AgroSciences, 10/12/02).